

# Precise Time and Time Interval, Astrometry and Astrophysics

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## LONG-TERM GOAL

This program develops, implements, and tests, on telescopes and precise time systems, technologies for the determination of the positions and motions of celestial bodies, the motions of the Earth, and precise time in order to provide the astronomical and timing data required by the Navy and other components of the Department of Defense (DoD) for navigation, precise positioning, command, control, and communications, as well as developing sensor systems for surveillance. The primary goal is to improve the accuracy, quantity, timeliness, and reliability of the operational support provided by the U.S. Naval Observatory (USNO) to DoD in the areas of precise time and time interval, Earth rotation and orientation, and inertial reference frames based on star, planet, and extragalactic source positions. Further technologies will be developed to improve sensor technologies for surveillance, targeting, and navigation.

## OBJECTIVES

The USNO Mission, as the only U.S. institution engaged in the practical application of astrometry and timekeeping, is to provide DoD with precise time and celestial position data and also to promulgate such data as directed by public law through the publication of the astronomical ephemeris. The R&D supported by this area allows the USNO to fulfill its operational mission responsibilities in a field which has an ever evolving technology in sensors, communications, systems control, and analysis. Specific objectives of this program include:

- Improvement of the U.S. Master Clock systems both in Washington and at Schriever AFB, the master control station for GPS, by evaluating and incorporating new types of clocks, real-time clock monitoring systems, and time scale algorithms for clock ensembles.
- Evaluation and refinement of various time transfer (clock synchronization) techniques especially using GPS in order to provide and sustain a tightly coupled worldwide DoD time system.
- Improvements to the fundamental ephemerides, which are the bases for positions of solar system bodies and the fundamental stellar reference system.
- Improvements to the algorithms for artificial satellite motions and their orbits especially in the area of GPS orbits in order to improve the accuracy of UT1 and polar motion.

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- Improvement in the models and algorithms used for Earth rotation and orientation predictions to fulfill DoD systems autonomy requirements.
- Improvements to astronomical reference frames based on star, planet, and quasar positions, including increases in precision, benchmark density, and inertial stability.
- Development of radio/IR/optical interferometry and charge coupled device (CCD) technology for precision astronomical measurements, including satellite tracking applications, and expansion of precision star catalogs to the infrared wavelengths by exploiting IR technology.

## **APPROACH**

The cesium fountain has met its short-term performance goals, and we have analyzed the medium- to long-term performance up to several days. Various methods of time transfer—worldwide clock synchronization to UTC (USNO)—must be evaluated. DoD users operationally get their time directly from GPS (UTC (USNO)) at the 30 to 1000 nsec level. However other techniques can yield substantial improvement. GPS common view provides absolute synchronization at the 10 nanosecond level, but other methods, including carrier phase GPS tracking, laser reflection, fiber transmission, global broadcasting, the Wide Area Augmentation System (WAAS), and two-way radio transmissions, in some cases have demonstrated the ability to provide synchronization at the nanosecond, or better, level. All of these techniques need further refinement for use in operational systems.

The existing R&D device will be completed to perform long term evaluations that are referenced to the USNO Master Clock. Work will accelerate on a second, more heavily engineered R&D fountain. This device will be built with rubidium atoms (to lower collisional frequency shifts). We will be investigating alternate laser synthesis methods for trapping and cooling the atom, and building the vacuum chamber and microwave interrogation regions.

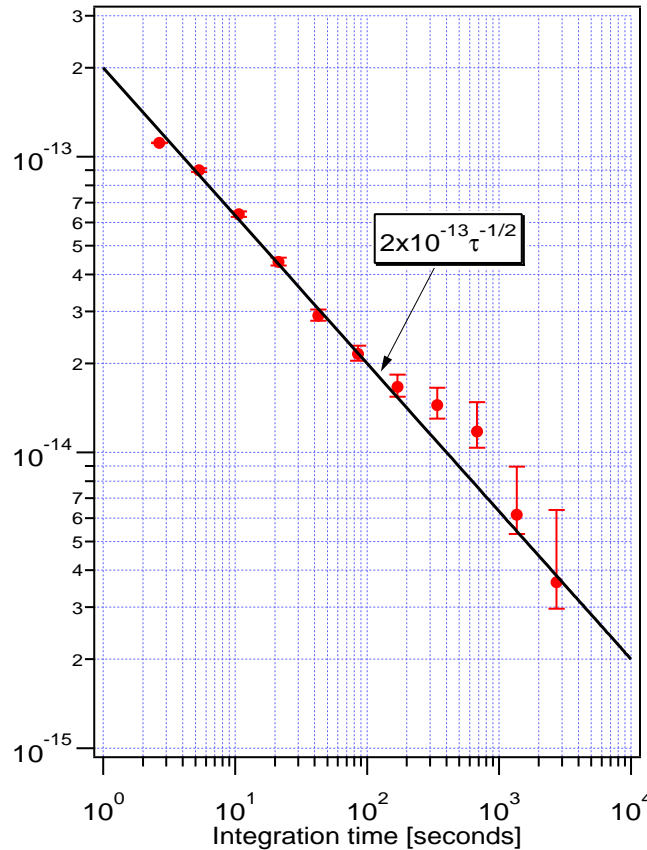
At optical wavelengths, CCD device applications to astrometry are underway. These devices, of high quantum efficiency, dynamic range, and linear response, promise to revolutionize many types of astronomical observations. Development of hardware and software for CCD detection systems suitable for high precision star positions is a major focus of work at USNO's Flagstaff station.

A new approach to determine very accurate star positions with such detectors on a stationary telescope, the Sloan Digital Sky Survey (SDSS), covering one quarter of the entire sky, is being investigated. The SDSS is scheduled to begin routine survey operations this FY. Once underway, this survey will begin to generate accurate astrometric positions for stars from magnitude 13 to nearly magnitude 23 over a significant fraction of the sky. A 1.3 m wide field telescope is being developed for Flagstaff.

A space base mission has been developed. This mission, Full-Sky Astrometric Mapping Explorer (FAME), will fly 24 2k x 4k CCDs. NASA will support the FAME mission for a 2004 launch. Research on the capability of a CCD focal plane to make precise measurements under space conditions has been and continues to be supported under 6.2 funding.

## WORK COMPLETED

The short term performance of the cesium fountain has been improved to levels as good as  $1.5 \times 10^{-13} / \sqrt{\tau}$ . Work on many aspects of the device has resulted in continuous operation for up to 10 days. In addition, operation has been demonstrated with a steered hydrogen maser as the output of the fountain. When operating with a steered output, the fountain detected and removed the drift of the maser at the level of better than  $2 \times 10^{-16} / \text{day}$ .



**Figure 1. Demonstration of Stability of the Cs Fountain**

*(The Allan deviation achieved with the Cs Fountain steering a hydrogen maser. When operating with the steered output, the fountain detected and removed the drift of the maser at the level of better than  $2 \times 10^{-16} / \text{day}$ .)*

The program in GPS carrier phase time transfer has demonstrated production of continuously filtered clock products. In addition the research effort has produced an improved IGS (International GPS Service) timescale product that is under initial release. This scale routinely produces a globally distributed time scale with a frequency stability of  $2 \times 10^{-15}$  at one day.

USNO is working with NAVSYS to develop a 16 element phased array antenna working with a dual frequency 12 channel GPS P/Y code time monitor station receiver. The addition of the phased array antenna will allow for much improved receiver measurement noise because of an almost 12 db

increase in S/N and much reduced multi-path due to the directional nature of the antenna. This system should also allow for real time GPS carrier phase ambiguity resolution that should lead to picosecond level time transfer. In the spring 2001, NAVSYS conducted an early demonstration of the receivers ability to use the 16 element phased array antenna to improve the measurement noise by >10 db. A full demonstration of the receiver capabilities is scheduled for November 2001. If funding is available in FY02, USNO would procure a second antenna/receiver system and conduct a series of picosecond level time transfer demonstrations. Also the technology developed will most likely be used as part of GPS III at the improved GPS monitor stations.

USNO, working with JPL, has conducted a series of “real time” time transfer experiments that show the potential of <100 picosecond time transfer anywhere in the world. As part of this effort USNO is now providing the time reference for the NASA/JPL global interneted differential GPS system. Given sufficient funding, USNO should be able to conduct a series of time transfer demonstrations that will show 100 picosecond time transfer to a moving airplane or other vehicle. This demonstration will be critical to the DOD community because 100 picosecond time transfer to a moving platform implies sub-meter target location errors for a surveillance platform.

At the beginning of the fiscal year the SDSS telescope and instrumentation were officially dedicated at Apache Point Observatory, New Mexico. SDSS operations, including both imaging and spectroscopic observations, as well as pipeline software data reduction, are now routine. Over 2,500 square degrees of the survey area have now been scanned, and spectra have been obtained for over 150,000 objects. In June 2001, SDSS made its first public release of data, consisting of over 450 square degrees and 50,000 spectra. Image quality has been improved, due largely to better control of the thermal environment of the telescope, and the telescope is now dependably delivering resolution that meets the scientific requirements.

The 1.3 m wide field telescope is being developed for wide field astrometric applications. This telescope will be fully automated and equipped with a camera containing six 2k by 4k CCDs. Fabrication of this camera will be completed by February 2002. At present the telescope is being operated with a camera containing a single 2k by 4k CCD. Engineering tests evaluating the telescope focus and collimation as well as thermal control to reduce distortions in the primary mirror due to day/night temperature changes have been completed. Astrometric observations of stars and geosynchronous satellites have been initiated. The software for automated telescope operations are under development. Significant USNO/astrometry highlights included:

- The astrometric software pipeline, developed and maintained by USNO astronomers, has proven to be very reliable and robust. No major changes to the pipeline were needed this year, although some enhancements have been made, primarily in the areas of quality analysis and error analysis.
- Astrometric performance consistently falls well within the scientific requirements. The internal errors are typically 60 milliarcseconds per coordinate (rms) when USNO CCD Astrographic Catalog (UCAC) coverage is available for a scan, and better than 100 milliarcseconds per coordinate (rms) when UCAC coverage is not available and the Tycho2 catalog is used.
- USNO astronomers wrote software to help the observational team predict telescope tracking difficulties (high rates of motion for the telescope axes) and to monitor the telescope tracking performance in real-time.

The CCD development for FAME is progressing. There have been difficulties in fabricating the CCDs. Delivery of the thinned CCDs is expected in October 2001. Laboratory tests will take place in FY02.

## RESULTS

The cesium fountain has demonstrated continuous operation with a steered output for up to 10 days with a short-term stability of  $1.5 \times 10^{-13}$  at one second. The GPS carrier phase project has produced a globally distributed time scale with a stability of  $2 \times 10^{-15}$  at one day.

The USNO project to develop a new 12 channel GPS P/Y code time monitor station (TTR-12) is nearing completion. USNO stability testing shows that the new TTR-12 receiver is a factor of ten more stable relative to the present USNO GPS time monitor station receivers. In September 2001, two TTR-12 receivers were made operational as part of USNO mission to provide the time reference for the GPS system. We anticipate that early in 2002 that USNO will completely switch all GPS time monitor operations to the TTR-12. This should lead to improved time synchronization to USNO for both DOD and civil users of GPS. Several significant and very exciting scientific discoveries have already come from the first 1-1/2 years of survey operations.

- The Survey has now found the large majority of all known high-redshift Quasars, including the current record holder with a redshift of 6.28.
- Numerous “brown dwarf” stars have been discovered.
- Several Galactic structure studies are underway that are producing very interesting results concerning the distribution of stars in our Milky Way Galaxy, which gives clues to its formation history.
- The Survey is discovering significant numbers of Carbon stars (stars whose spectra show strong features from molecular carbon). USNO is determining the proper motions of these objects using our database of digitized photographic plates.

## IMPACT/APPLICATION

In the area of precise time and time interval the stability of the Master Clock is now about 1ns rms/day. This stability will be improved by two orders of magnitude through the use of a Rubidium Fountain. This development will lead to time performance at the 100 picosecond level. Improvements in time transfer at this level are also being developed via GPS carrier phase time transfer, GPS receiver and antenna technology, and the WAAS. With this long-term stability and accuracy in time it appears promising to achieve worldwide time stability on the nanosecond level and the resulting accuracy in navigation and targeting of precise munitions should approach the one-meter level. In the area of astrometry, the development of large format CCD focal plane arrays will bring forward the determination of precise positions of a large number of stars. Space astrometry will yield the precise positions of stars at the submicroarcsecond. These star positions are needed for present and future DoD space operations. This will allow these objects to be employed for the precise determination of satellite positions, improved geolocation, and space navigation.

## TRANSITIONS

Due to the unique role of the USNO as the standard for Navy and DoD Precise Time and Time Interval (PTTI) operations, every successful exploratory development study leads immediately to an improved operational capability. As was stated last year the 6.2 technology development emphasis is shifting to developing improved time standards and time transfer. The successful development of the TTR-12 receiver will improve GPS time. In the area of earth orientation parameters, the determination of UT1 and polar motion has transitioned from 6.2, via 6.4 into operations.

## RELATED PROJECTS

This research is highly coordinated with work performed nationally and internationally. The clock work is coordinated with programs at NIST in the US, BIPM, LPTF and Ecole Normal Superior in France and the PTB in Germany. The astrometry work is coordinated with research at universities and national facilities such as the National Radio Astronomy Observatory (NRAO) and the National Optical Astronomy Observatory (NOAO). For example the program to develop the InSb detector array is a joint effort with NOAO. The development of large focal plane arrays for astrometry at optical wavelengths is being pursued in a joint program, the Sloan Digital Sky Survey (SDSS), with the Astrophysical Research Consortium (members Princeton, Universities of Chicago, Washington, Fermilab).

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